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Barrio, Samantha Caporal Del; Pelosi, Mauro; Franek, Ondrej; Pedersen, Gert Frølund

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Coupling Element Antenna with Slot Tuning for Handheld Devices At LTE Frequencies

Samantha Caporal Del Barrio*, Mauro Pelosi*, Ondrej Franek*, Gert F. Pedersen*
*Section of Antennas, Propagation and Radio Networking (APNet), Department of Electronic Systems,
Faculty of Engineering and Science, Aalborg University, DK-9220, Aalborg, Denmark
{scdb, mp, of, gfp}@es.aau.dk

***Abstract*—Tunable antennas are a promising way to overcome bandwidth limitations for the new communication standards. Since it is the chassis that resonates in the low frequencies, its tuning is pertinent and allows for more compact size designs. This paper proposes a coupling element based antenna. A reconfigurable slot is inserted in the ground plane in order to lower its resonance frequency. The tuning is done by a capacitor across the slot. It is shown that covering all frequencies between the 900-GSM band and the 700-LTE band can be achieved. The radiating structure also presents a resonance in the high LTE band which is unaffected by the tuning mechanism of the lower band. Moreover, the efficiency can be optimized by an analysis of the currents across the slot. The study also shows that holding the device does not lead to additional mismatch losses which will further improve the overall efficiency.**

Keywords— Tunable Antenna, Coupling Element, Slot Antenna.

I. Introduction

A strong trend in the mobile telecommunication technology is to significantly decrease the size of the handsets. Miniaturization can be achieved by efficient designs as multi-band structures, high dielectric loading or non-resonant antennas [1]-[7]. The non-resonant antennas are designed in order to properly excite certain radiation modes of the ground plane rather than self resonance [8]-[10]. Their main advantage is to be low-volume and low-profile. Nevertheless separate matching circuitry has to be used to match the resulting antenna to the 50 Ω feed line at the desired resonance frequency. Thus a drawback of such technique is the losses introduced by the lumped components [6],[7],[11], especially for low frequencies as 700 MHz.

For the next Long Term Evolution (LTE) standard, the mobile terminals will need to operate in 23 frequency bands between 700 MHz and 2.6 GHz. Among other techniques, reconfigurability provides tuning over a wide range of frequencies without requiring additional space for the antenna. Slot antennas are a good candidate for compact tunable antennas and have the convenience of tuning the resonance frequency across the slot. This paper presents a compact and simple reconfigurable antenna combining coupling elements and slot tuning techniques. In Section II, the geometry of the radiating structure is described. Simulated results are presented in Section III investigating the tuning range and influence of the tuning capacitor on the losses. Section IV presents the user's influence on the design. Finally conclusions are drawn in Section V.

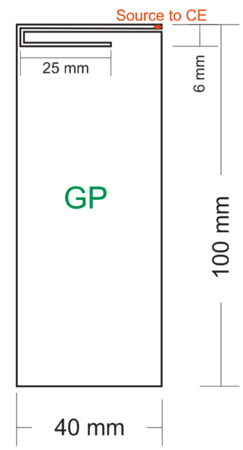

Fig. 1. Ground plane geometry.

II. Antenna Design

Even though the proposed design is based on a coupling element excitation, there is no external matching circuitry. A slot in the Ground Plane (GP) is used instead. This is done in order to lower the resonance frequency of the radiating structure preventing losses from lumped components, overall when the structure is being tuned.

A. Geometry

The GP size is 100×40 mm^2 and it has a resonance close to 1.1 GHz. These dimensions correspond to the ones of a typical candy-bar phone. A coupling element (CE) is placed at a distance of 2 mm above the GP. The CE is a square of 4x4 mm^2. A slot is inserted in the GP to lower the resonance frequency of the overall structure. The slot is not directly fed, the source is connected to the CE. The designed slot is an open-ended slot type since with the same physical length of the slot the resonant frequency can be doubled by opening one of its ends [12]. Additionally, the slot itself resonates which creates a second resonance covering the high LTE band around 2.6 GHz. The resulting dual band radiating structure is shown in Fig.1 and has a Quality factor (Q) of 26 at 1 GHz. Between the 700-LTE band and the 900-GSM band the coverage is ensured by a tuning mechanism. The resonance frequency is tuned towards lower values when the capacitance is increased.

B. Tuning

The slot in the GP is not fed by the source, therefore the currents running along the slot result from the coupling with the CE. The tuning capacitor is placed across the slot and in this configuration the currents running through the lumped component are expected to be small. This means that the losses due to the lumped component will be reduced, when increasing the capacitance and thus tuning towards lower frequencies. Because losses are expected when the capacitance value increases, having low currents through the capacitor is important from an efficiency point of view. Nevertheless, the frequency shift ability is preserved and the tuning range wide. In order to achieve fine-tuning over the frequency bands, capacitance values below 1 pF are needed. The proposed design covers bands from 700-LTE to 900-GSM with 8 steps of 1/8 pF.

III. Simulations

A. Method

The described design was simulated with a Finite-Difference Time Domain (FDTD) method. Considering a uniform cubic lattice, a space step size of 1 mm was chosen, using perfectly matched layer absorbing boundary conditions. The Printed Circuit Board (PCB) and the CE were modeled as perfect electric conductors. The tuning capacitor was modeled as lossless.

B. Fields

Fig. 2 shows the $\mathbf{H}$ field magnitude normalized to 1 W on the chassis at 1 GHz. The scale is given in dBA/m so that the small variations of the field can be distinguished. From this plot it can be inferred that the tuning capacitor should be placed in a location close to the open end of the slot in order to minimize the currents running through it and therefore the losses due to the Equivalent Series Resistance (ESR) of the lumped component. However the frequency shift depends on the position of the capacitor as well. The lower the currents through it, the larger the shifts [13]. Hence, the tuning capacitor is placed at 15 mm from the open end of the slot on the PCB. The achievable tuning range is depicted in Fig. 3, also showing fine tuning between 1 GHz and 760 MHz.

C. Currents

The currents running through the capacitor vary with the capacitance value. In this section the currents will be calculated from the fields for different tuning stages and compared to one another. The goal is to see how much of the degradation of the efficiency is due to the tuning component, in both bands. For this reason the study focuses only on the first and the last tuning stages, i.e. 1/8 pF at 1 GHz and 1 pF at 760 MHz. The fields are simulated for a lossless component and the power loss will be calculated with an Equivalent Series Resistant (ESR). Since today's handsets transmit at a power between 1/4 W and 2

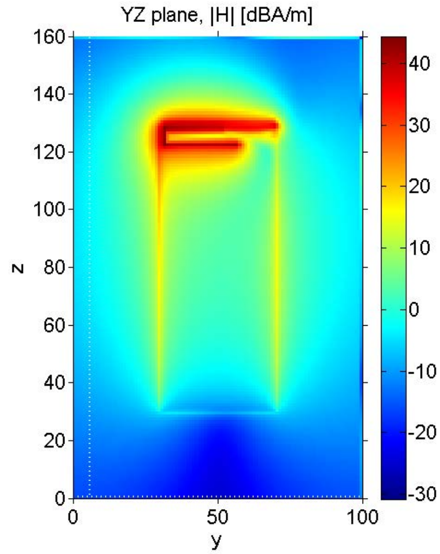

Fig. 2. $|\mathbf{H}|$ field on the PCB at 1 GHz.

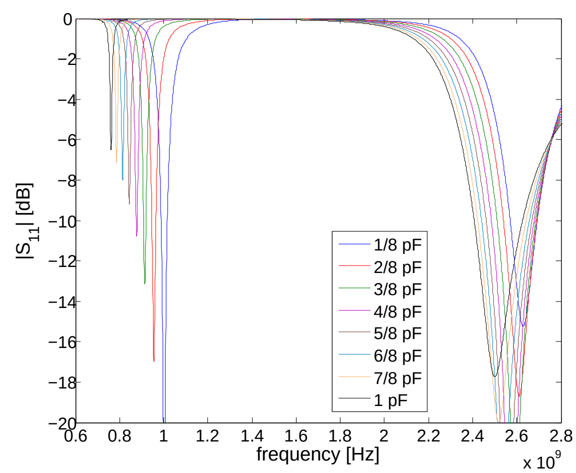

Fig. 3. Tuning range of the proposed radiating structure.

W [14] all values are normalized to 1 W input power hereafter.

1) High Band: For the first tuning stage the currents running through the 1/8 pF capacitor are :

$$I_{C(1/8pF)} = 35 \text{ mA, at 2.6 GHz.}$$

At the last tuning stage the currents running through the 1 pF capacitor are :

$$I_{C(1pF)} = 140 \text{ mA, at 2.6 GHz.}$$

2) Low Band: In the case where the lower resonance frequency is tuned to 1 GHz with the 1/8 pF capacitor the currents through the capacitor are :

$$I_{C(1/8pF)} = 75 \text{ mA, at 1 GHz.}$$

Typical values of ESR for high-Q series with capacitances below 1 pF are in the order of 0.4 ohms [15], which leads,

TABLE I

LOSSES OF THE PROPOSED ANTENNA DUE TO THE TUNING CAPACITOR

	1/8 pF		**1 pF**	
f$_r$	1 GHz	2.6 GHz	760 MHz	2.6 GHz
P$_{IN}$ [W]	1	1	1	1
P$_L$[mW]	2.2	0.5	350	7.8
η_r[dB]	$\ll$ -0.1	$\ll$ -0.1	-1.9	$\ll$ -0.1
V$_{bd}$[V]	79	$\ll$ 0.1	190	$\ll$ 0.1

for a practical case of 1 W input power, to a power loss in the capacitor of:

$$P_{L(1/8pF)} = 2.2 \text{ mW, at 1 GHz.}$$

At 750 MHz, when the lower resonance frequency is tuned with the 1 pF capacitor, the currents running through it are higher :

$$I_{C(1pF)} = 930 \text{ mA, at 760 MHz,}$$

leading thus to a power loss of :

$$P_{L(1pF)} = 350 \text{ mW, at 760 MHz.}$$

The radiation efficiency (η_r) is shown in TABLE I and the presented results are summarized.

D. Voltages

Breakdown voltage should also be taken into consideration while placing a capacitor for tuning. The breakdown voltage V$_{bd}$ is defined as :

$$V_{bd} = |E| \times \mathcal{D},$$

where $\mathcal{D}$ stands for the distance separating the two plates of the capacitor. In this section the V$_{bd}$ will be calculated for the tuning range boundaries : for the 1/8 pF case at 1 GHz and the 1 pF case at 760 MHz. The dimension of the tuning capacitor is 1 mm in the length and the width.

1) 1/8 pF: With a 1/8 pF capacitor the dielectric strength $|E_z|$ in the YZ plane leads to a voltage across the capacitor of 79 V. The breakdown voltage for the 1/8 pF capacitor in the proposed design, for 1 W input power is :

$$V_{C(1/8pF)} \geq 79 \text{ V.}$$

2) 1 pF: At 760 MHz the $|E_z|$ component in the YZ plane gives a voltage across the capacitor of V :

$$V_{C(1pF)} \geq 190 \text{ V.}$$

Typical values are between 40 V and 200 V [13]. The results are presented in TABLE I.

E. Measurements

The proposed antenna design has been built and the mock-up is shown in Fig. 4. The measurements were made in an anechoic chamber. The radiation efficiency was measured without tuning capacitor at 1 GHz and with a 1 pF fixed capacitor at 800 MHz. The efficiency is computed from a 3-D pattern integration technique, $\eta_{r(1GHz)}$ = -1.5 dB and $\eta_{r(800MHz)}$ = -3.2 dB.

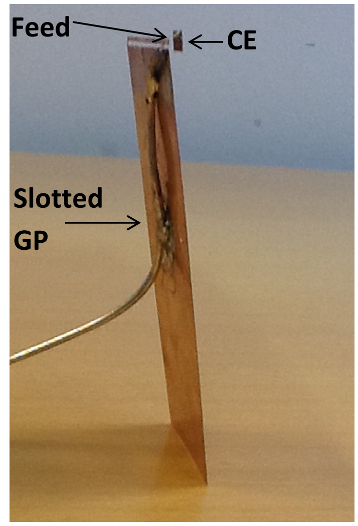

Fig. 4. Mock-up.

IV. USER INFLUENCE

As it is shown in [16] it is the user's hand that has the highest influence on the deterioration of the antenna performance in the proximity of a user, thus its influence is investigated on the proposed design. The results are computed for three cases: the high band, the high bound of the low band and the low bound of the low band. The High Band (HB) case is measured at 2.6 GHz, and the two low band cases are measured one at 990 MHz with a 1/8 pF capacitor and the other at 758 MHz with a 1 pF capacitor.

A. Hand Phantom

The study uses a realistic phantom hand with a relative permittivity of the body tissue ϵ_r = 36 and a conductivity σ = 0.8 S/m at 900 MHz [16]. The distance between the slot and the index finger is set to 10 mm, as the distance between the bottom of the GP and the palm, in order to model a typical thickness of a handset. The index finger is in a high E-field position due to the PCB geometry and additionally in a high H-field position due to the slot. Fig. 5 shows the hand grip on the coupling element based antenna with slotted ground plane.

B. Simulation Results

The absorption loss (L$_A$), the mismatch loss (L$_M$) and the total loss (L$_T$) are depicted in TABLE II. The capacitor is simulated as lossless to isolate the losses resulting from the user hand, for different frequencies and tuning stages. In all the cases L$_M$ is smaller or equal to 0.1 dB which means that the antenna resonance frequency does not suffer detuning from holding the phone. The HB and the smallest capacitance value 1/8 pF create a similar absorption loss about 2.5 dB but this value dramatically increases when the resonance frequency is tuned to the 700-LTE band. In the worst case the L$_T$ is 4.8 dB.

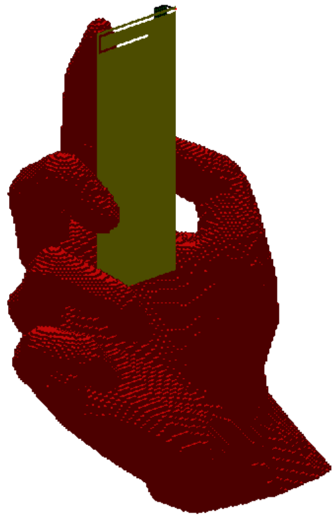

Fig. 5. Hand model.

TABLE II
LOSSES OF THE PROPOSED ANTENNA DUE THE USER HAND

	HB	1/8 pF	1 pF
f_r	2.6 GHz	990 MHz	760 MHz
L_M [dB]	0.1	$\ll 0.1$	$\ll 0.1$
L_A[dB]	2.3	2.5	4.7
L_T[dB]	2.4	2.6	4.8

V. CONCLUSION

In This paper a coupling element based antenna structure with slot tuning of the ground plane has been investigated. The chosen ground plane is a candy bar size one and the investigated frequencies are the low GSM and LTE bands, and the high 2.6 GHz LTE band. The coupling element is very compact, its dimensions are reduced to a square of 4x4 mm^2. The simulations show that fine tuning from the 900-GSM band to the 700-LTE band can be achieved with a capacitance range of 1 pF and steps of 1/8 pF. The tuning capacitor position is carefully chosen across the slot with a field investigation in order to reduce the losses it could generate. The currents running through the tuning capacitor are investigated since they are a source of loss in the radiation efficiency of the antenna structure.

The losses due to the tuning capacitor are calculated for a transmission power 1W, usual in today's use. The study shows that the highest losses are for the lowest tuned frequencies and therefore the highest capacitance values. Moreover the 1 pF capacitor is responsible for 1.9 dB of losses in the radiation efficiency at 760 MHz. This value is rather high and it is expected that the capacitor will be an important source of degradation of the handset performances.

The breakdown voltage is investigated as well, since it also determines the feasibility of the design. The expected voltages are below 200 V which is not an issue with the available components nowadays. Additionally a user's hand investigation is shown. The mismatch losses are below 0.1 dB and are negligible. The proposed design does not suffer from detuning when held. The absorption losses are up to 4.7 dB at the lowest tuned frequency. The design reaches more than 250 MHz fine tuning, at 760 MHz the 1 pF capacitor is responsible for 1.9 dB of losses and the user's hand contributes to the total losses with 4.8 dB.

Measurements have been made for the low frequencies of the tuning range. The predicted efficiency in TABLE I only took into acocunt the possible losses coming from the capacitor. The measured efficiency is lower than the prediction therefore other causes of losses are to be taken into account. Very low frequencies on small ground plane and high Q of the structure can lead to extra losses, as the poor Q of the components, the soldering or the irregularities of the mock-up.

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